THE WEATHER AND CIRCULATION OF JULY 1956[1]

Including Some Aspects of Momentum Flux in Relation to an Intense Polar Vortex

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1. WEATHER AND CIRCULATION IN THE UNITED STATES

The prevailing westerlies of middle latitudes were north of normal over eastern North America during June 1956 [1]. During July, however, they shifted southward again, to a latitude more typical of May (compare fig. 6 of [1] with fig. 1A of this article). This abnormal southward displacement of the westerlies brought below normal temperatures and frequent cyclonic activity, accompanied by prolonged cloudiness and precipitation, to the northeastern quarter of the nation.

This July was the coldest in over half a century for eastern Pennsylvania, and parts of New York State, New England, and Michigan. In the Northern Plains monthly mean temperature anomalies of 4° F. below normal were the lowest in over forty years at several stations. At some localities in the northern part of the country afternoon temperatures barely climbed above 80° F., while at Sault Ste. Marie, Mich., the highest temperature was only 78° F.—the lowest for any July. Minimum temperatures in the low forties were not uncommon, with some rural areas in the lower peninsula of Michigan even reporting frosts.

These subnormal temperatures were for the most part situated in an area of below normal 700-mb. heights (fig. 2), just north of the mean frontal position (fig. 3) and the largest wind speed anomalies (fig. 1B). Compared with July 1955 [2], this month was diametrically opposite in circulation pattern over the eastern part of the country. Then, the strongest westerlies, mean frontal zone, and principal storm track were displaced north of the Canadian border, while temperatures ranged as high as 4°–6° F. above normal.

July 1956 was also one of the cloudiest and rainiest on record for much of the northeastern quarter of the nation with many stations reporting rain (including trace) on 20 or more days during the month. Note the large number of days with fronts (as many as 23) over Kentucky and Virginia in figure 3. Yet, monthly rainfall totals for some communities were not unusually great and, in a few places, were even subnormal. For example, at Scranton,

Pa., there occurred 23 days with rain, but the monthly total of 3.18 inches was 2.15 inches below normal.

The frequent storminess responsible for this cool, rainy weather can be seen from the cyclone tracks of Chart X.
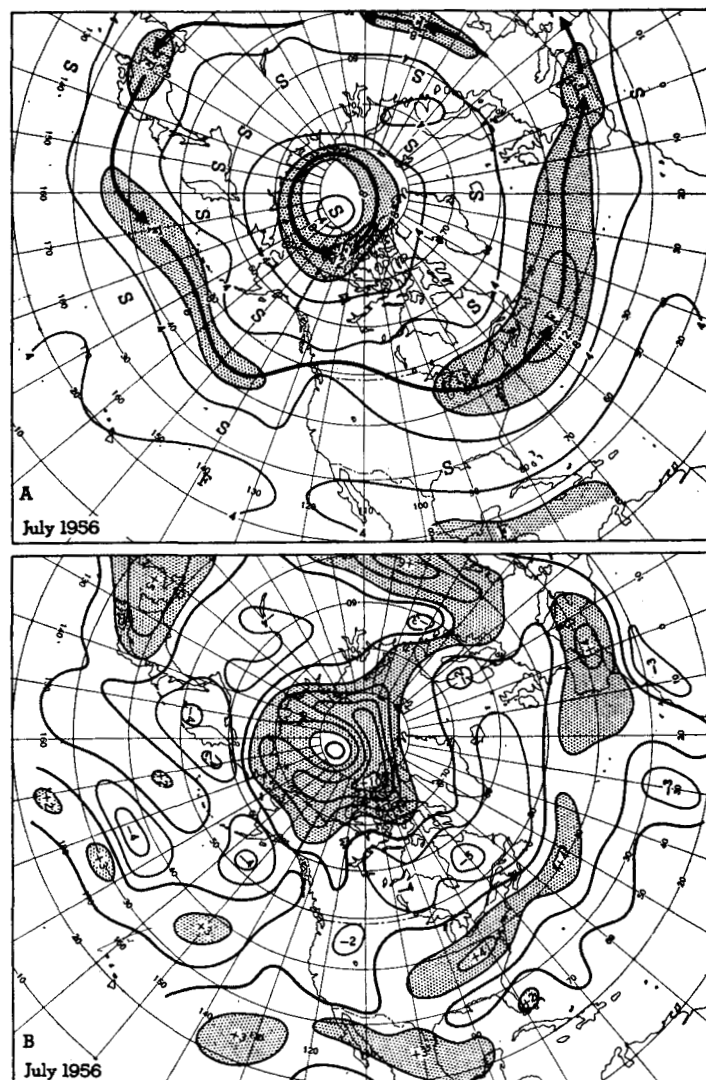

FIGURE 1.—(A) Mean 700-mb. isotachs and (B) departure from normal wind speed (both in meters per second) for July 1956. Solid arrows in (A) indicate axis of the mean jet stream at 700 mb. Wind speeds in (A) greater than 8 m. p. s., and wind speed anomalies in (B) greater than 4 m. p. s. are shaded. Note the strength of the circulation in the Arctic.

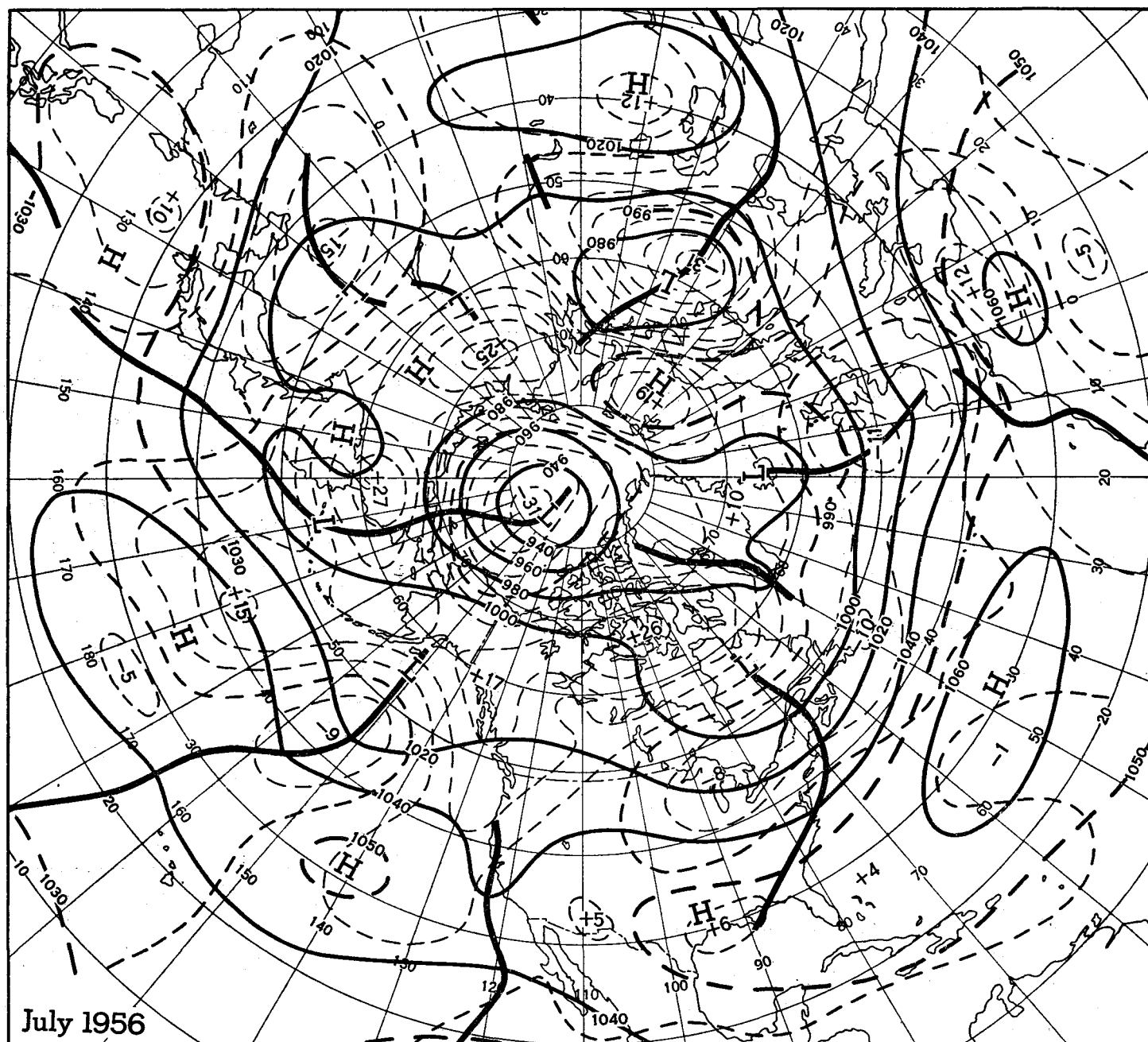[1] See Charts I-XVII following p. 289 for analyzed climatological data for the month.

FIGURE 2.—Monthly mean 700-mb. height contours and departure from normal (both in tens of feet) for July 1956.   The deep polar vortex and its surrounding ring of positive height anomalies are notable features.

Several times, as the meandering belt of westerlies dipped south across the Canadian border, deep, closed Lows formed and, steered by the mean flow (fig. 2), moved slowly southeastward toward the Lakes.[2]   Frequent passage of migratory polar anticyclones over the northeastern quarter of the country (Chart IX) was also responsible for cool weather in that sector.

In contrast to the Northeast, warm, dry weather accompanied above normal 700-mb. heights over Texas and Louisiana as well as in the extreme western part of the

country (Chart I-B and fig. 2).   Fort Worth, Tex., with an average maximum temperature of 101° F. and a monthly mean of 89° F., reported this month as the second hottest on record.

Below normal temperatures over the Southwest can in part be related to the rather general cloudiness and rainfall that occurred (Charts III, VI, VII).   However, some of the cooler days received the maximum possible sunshine.   This was generally true early in the month when the moisture content of the air was low and a strong diurnal range of temperature occurred with low nighttime minima.   Stronger than normal northwesterly flow on

[2] See article by McQueen and Martin in this issue for a discussion of one such synoptic situation.

the monthly mean sea level map (Chart XI and inset) was also indicative of cool weather in this area.

2. CIRCULATION AND WEATHER IN OTHER PARTS OF THE NORTHERN HEMISPHERE

The mean circulation for July 1956 was characterized by stronger than normal westerlies in the Arctic and in mid-latitudes with subnormal values in the zone between (fig. 1). This latitudinal distribution of wind speed was associated with a belt of above normal 700-mb. heights completely circumscribing an unusually intense polar vortex (fig. 2). Positive height anomalies in this ring included centers of 270 ft. over northeastern Siberia and 260 ft. over northern Canada. These were indicative of the persistent blocking anticyclones that formed within this belt. The polar vortex, with an extreme height anomaly of −310 ft., was a site of frequent and sometimes intense cyclonic activity. On its periphery, mean 700-mb. wind speeds reached values as high as 12 m. p. s., or 10 m. p. s. above normal (fig. 1).

Cyclonic activity was also typical of the regions of subnormal 700-mb. heights south of the circumpolar ring of high pressure, and Lows forming in these regions reached unusual intensities for this time of year and these latitudes. This month, with its large, deep, and often slow-moving vortices over the east-central Pacific, the Great Lakes region, the British Isles, and Russia, seemed more typical of spring than summer.

The largest negative height anomaly (−310 ft.) was that over Russia, where a large closed Low center was present even on the monthly mean 700-mb. map (fig. 2). Some of the coldest temperatures with respect to normal for the lowest 300 mb. of the troposphere occurred here as well as considerable rainfall. A trough extending from this center southward to the Persian Gulf was particularly well marked over Iran, where it caused flood-producing rains.

Heavy rains also fell in a center of negative height anomaly (fig. 2) over the British Isles. This precipitation was associated with numerous storms travelling across the Atlantic on a track depressed south of normal (Chart X). These rains were reported as being the heaviest in 80 years—an unusual contrast to May which was the driest since 1860.

In the eastern Pacific a trough and below normal heights appeared in a region that is climatologically favorable for ridges. Only one other July (1950) in the past 22 years has had a trough in this location. Development of this trough accompanied rising 700-mb. heights over the Bering Sea and Alaska as blocking shifted westward from Canada. Concurrently there was a slow weakening of the climatologically favored trough along the west coast of North America. This latter trough did not reintensify until the Pacific High was again established at the end of the month.

3. EVOLUTION OF THE JULY CIRCULATION

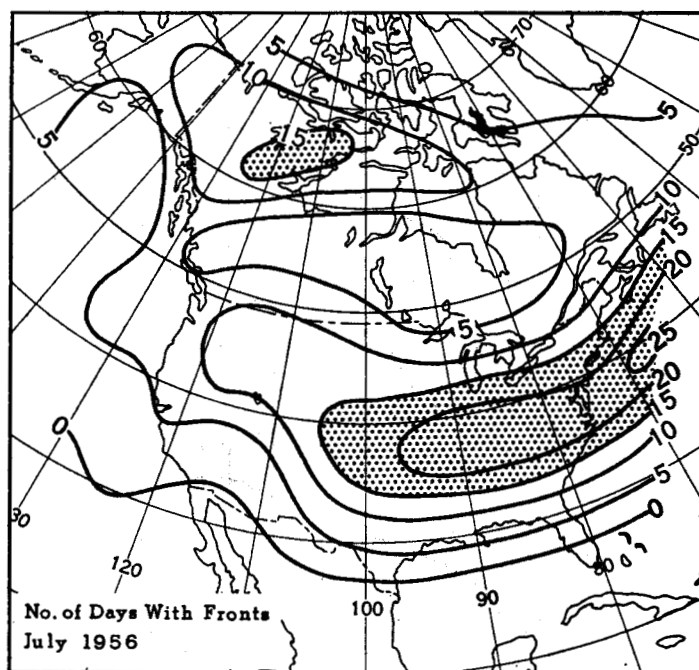The development of this month's circulation is well

FIGURE 3.—Number of days in July 1956 with surface fronts of any type (within squares with sides of approximately 500 miles). Frontal positions taken from *Daily Weather Map*, 1:30 p. m. EST. The unusually high frequency of fronts over the eastern part of the country was responsible for cool, rainy weather.

portrayed by a series of 15-day mean zonal wind speed profiles (0° westward to 180° long.) from the period May 16–30 to July 16–30 (fig. 4). Reference to the first two graphs (fig. 4A and B) shows a jet at mid-latitudes strengthening to an average value of 12 m. p. s., accompanied by a marked increase in the north-south shear across the current. This strong zonal flow, however, was unstable and "split" into two branches during the first half of June. At this time a locus of cyclonic activity near Novaya Zemlya shifted into the polar cap—its impression on the mean zonal flow being indicated by the weak polar jet appearing at high latitudes (fig. 4B). This polar vortex underwent significant intensification the latter half of June (fig. 4C), while on its periphery the increasing anticyclonic shear was accompanied by rising pressures and a weakening of the zonal flow. Concurrently, the jet at mid-latitudes edged south and weakened about 3 m. p. s. This pattern, once established, persisted into the first half of July with a slight weakening of the polar jet and a strengthening and southward shift of the one at mid-latitudes (fig. 4D). By the end of July (fig. 4E) a significant weakening of both jets took place, accompanied by increasing westerlies near 60° N. as the two currents approached one another. Over the Middle Atlantic States, however, the westerlies continued strong with no improvement in the weather.

4. MOMENTUM TRANSFER AT HIGH LATITUDES

The maintenance of westerlies in any zonal ring requires a transfer of angular momentum into that ring to compen-
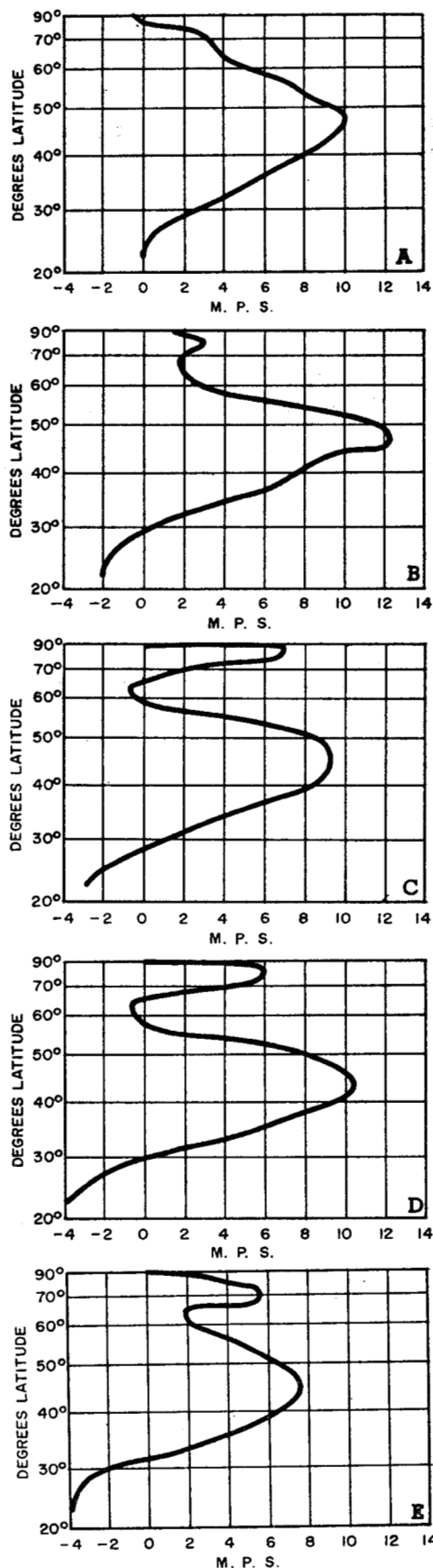
FIGURE 4.—15-day mean zonal wind speed profiles for the Western Hemisphere at 700 mb. for (A) May 16–30, (B) May 30–June 13, (C) June 16–30, (D) June 30–July 14, and (E) July 16–30, 1956. Note development of double jet in June and its persistence through July.

sate losses due to friction. This momentum is supplied by the surface easterlies (essentially the trade wind belt) which receive westerly momentum from frictional interaction with the earth [3]. Variations in the zonal momentum at a given level result from the effects of: (1) horizontal convergence of relative angular momentum, (2) vertical convergence, (3) mean meridional circulations, (4) friction, and (5) mountain torques. Of these, the first has been considered one of the most important sources for the westerlies. It is also the most easily measured and can be computed from constant pressure charts using the geostrophic assumption.

Considering the strong westerlies in the Arctic and in mid-latitudes this month with blocking activity in the zone between, it was thought interesting to compare fluctuations of the zonal momentum for various belts with the horizontal flux of relative angular momentum into these belts. This was carried out for the polar cap (region north of 75° N.) and the zonal ring from 55°–75° N. Time did not permit a more extensive study.

Starting with the relationship [4]

$$T = \int_0^{2\pi} \rho R^2 \cos^2 \varphi \, uv \, d\lambda \tag{1}$$

where T_φ is the horizontal transfer of relative angular momentum across latitude φ, R is the earth's radius, ρ is the density of the air, u and v are respectively the eastward and northward components of the horizontal wind flow, and λ is the longitude, one can employ the geostrophic assumption and evaluate the above integral numerically to obtain

$$T_\varphi = K \sum_{\lambda=0}^{360} (\Delta z)_\varphi (\Delta z)_\lambda \tag{2}$$

where K is a constant for the latitude in question, and $(\Delta z)_\varphi$ and $(\Delta z)_\lambda$ are the north-south and east-west contour height differences respectively. For this study these were obtained from heights 5° north and south (or east and west) of the given point, and the summation of products was then taken around a parallel of latitude. The data used were 5-day mean 700-mb. heights centered four or five days apart during June and July. Such computations have been made on 5-day mean 700-mb. charts previously for other cases [5, 6]

The results of applying equation 2 at 75° N. are shown in figure 5 (top). For comparison, the zonal wind speed for the polar cap, where a mean Low was located from June 4 to the end of July, has also been plotted in figure 5 (bottom). This figure indicates that: (1) During this period the convergence of momentum into the polar cap was essentially positive, averaging about 4×10^{18} gm. cm. sec.$^{-2}$; (2) The long-period trend of zonal wind speed in the polar cap, and that of momentum flux across 75° N. were both downward, especially during July; and (3) Variations in the two curves can be related. This would suggest that the polar vortex was largely maintained by a flux of momentum across its boundaries, which was
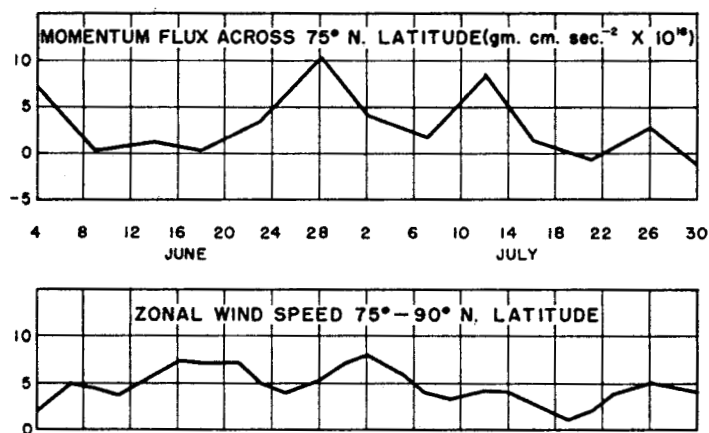
FIGURE 5.—Upper curve.—Momentum flux at 700-mb. level across 75° N. (gm. cm. sec.$^{-2} \times 10^{18}$). Lower curve.—Zonal wind speed at 700 mb. for the belt 75°–90° N. (m. p. s.). Momentum flux into the polar cap was essentially positive.

probably achieved by the numerous travelling cyclones that moved into the Arctic during this period. Tracks of several of these are portrayed in Chart X, and many others were also noted in the Eastern Hemisphere.

Agreement between the two curves is poorest about June 16 and July 22. At these times there occurred strong responses of the zonal wind speed to small values of the momentum flux. This points to other important sources of momentum for the 700-mb. level, such as vertical momentum convergence, effects of mean meridional circulations, or mountain torques due to the Greenland plateau.

The best agreement between the two curves is between June 24 and July 15, which may be a period when the contribution from other sources was least. During this period both maximum and minimum values of zonal wind speed $\left(\frac{\partial u}{\partial t}=0\right)$ occurred with a value of the momentum flux of approximately 5×10^{18} gm. cm. sec.$^{-2}$. This may perhaps represent a rough measure of friction for this interval.

A better method of studying the polar vortex would be to calculate the momentum flux across the boundaries of the vortex itself, as suggested by Starr [7], rather than across fixed latitudes. However, time did not permit this to be done here.

The next zone that was examined was the 55°–75° N. latitude belt which, it will be recalled, was one of high pressure completely surrounding the pole on the July mean map (fig. 2). As a measure of the momentum convergence into this belt, the difference between the flux across 55° N. and that across 75° N. was obtained (fig. 6, top). Comparing this curve with the zonal wind speed for the belt (fig. 6, bottom) reveals fair agreement, with periods of relatively strong momentum convergence into the belt accompanied and followed by stronger zonal wind speeds, and periods of divergence (negative values of the flux difference) by weak winds. The periods of
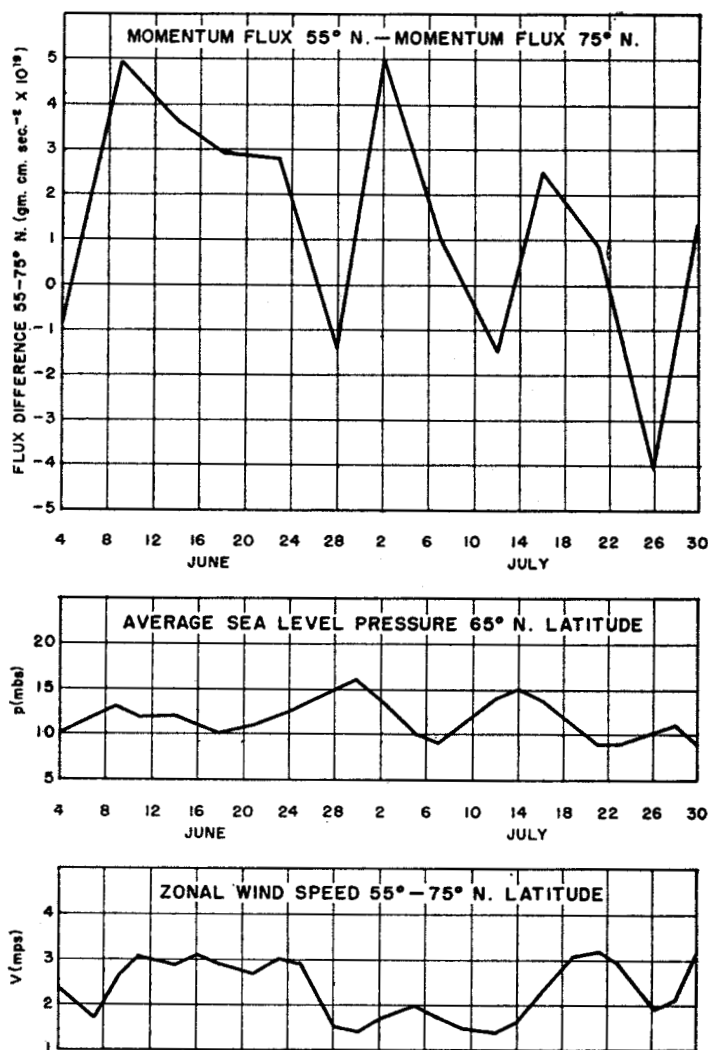

FIGURE 6.—Upper curve.—700-mb. momentum flux at 55° N. minus that at 75° N. (gm. cm. sec.$^{-2} \times 10^{19}$). Middle curve.—Average sea level pressure (mb.) at 65° N. Lower curve.—700-mb. zonal wind speed (m. p. s.) 55°–75° N. Note tendency for small and negative values of the convergence to be accompanied by rising pressure and decreasing wind speeds.

strong divergence of momentum in the 55°–75° N. belt (note sharp dips in fig. 6, top, on June 28, July 12, and July 26) were periods of strong momentum accumulation in the polar cap (note sharp peaks in fig. 5, top). However, only about 40 percent of the momentum lost by the 55°–75° latitude belt was transported north across 75° N. The remainder was transported southward across 55° N. into the belt of strongest westerlies. Of interest is the long-period downward trend of momentum convergence during July and the corresponding upward trend in the zonal motion for the belt. This again points to other important sources of momentum.

The variation in sea level pressure within the 55°–75° N. belt (fig. 6, middle) shows momentum flux divergence accompanied by increasing pressure, and convergence accompanied by decreasing pressure. This relationship is expected, since it is well known that a tendency exists for

the zonal wind speed to vary inversely as the pressure within the given belt [8, 9]. Rising pressure in this belt also accompanied a convergence of momentum into the polar cap with a tendency for the pressure to reach a maximum after the momentum convergence.
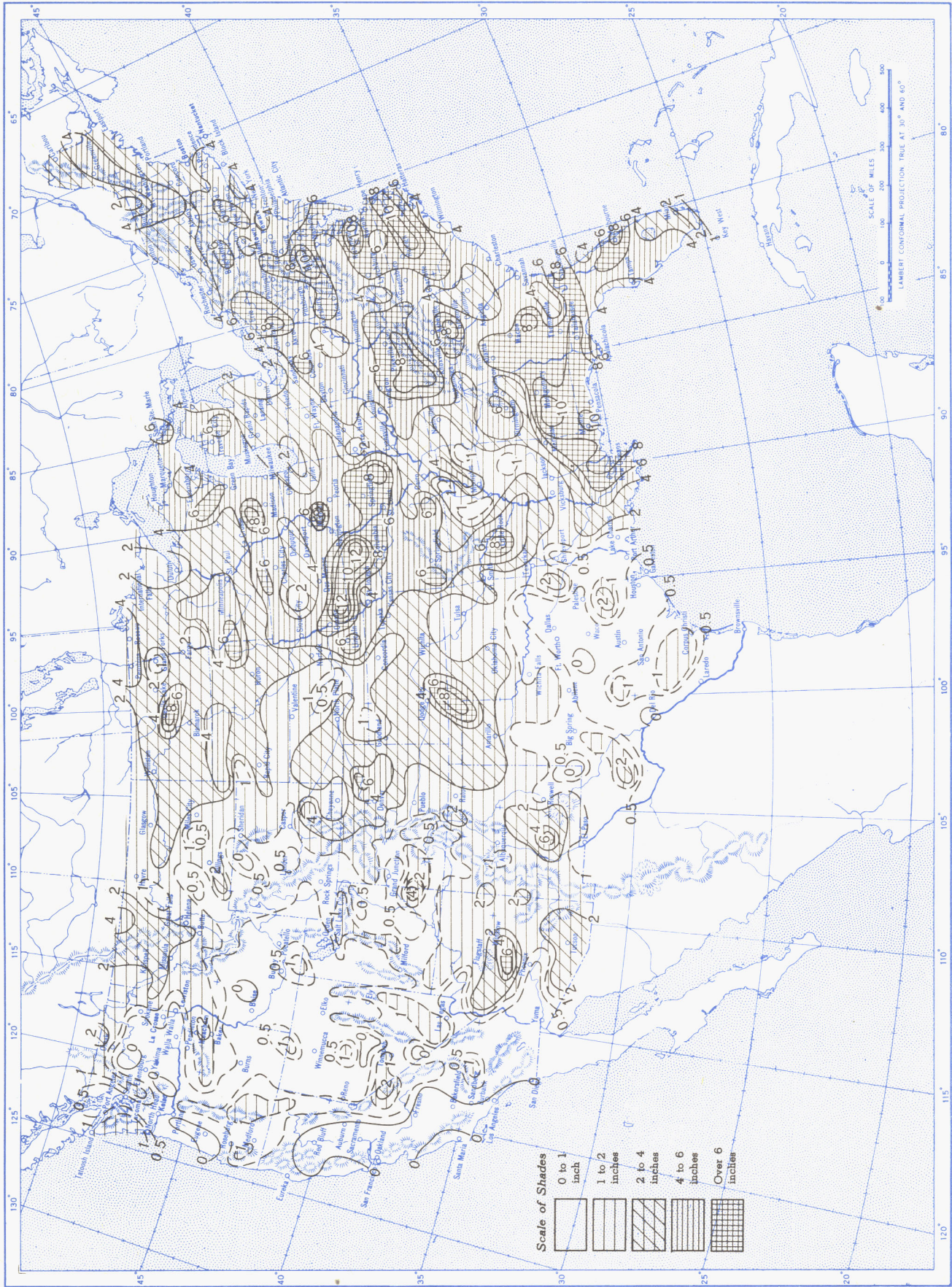
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3. V. P. Starr, "An Essay on the General Circulation of the Earth's Atmosphere," *Journal of Meteorology*, vol. 5, No. 2, Apr. 1948, pp. 39–43.
4. W. K. Widger, Jr., "A Study of the Flow of Angular Momentum in the Atmosphere," *Journal of Meteorology*, vol. 6, No. 5, Oct. 1949, pp. 291–299.
5. W. G. Leight, "Some Possible Applications of Momentum-Transport Theory," *Journal of Meteorology*, vol. 11, No. 1, Feb. 1954, pp. 10–15.
6. W. H. Klein and W. G. Leight, The Usefulness of Momentum Flux for Predicting the Zonal Westerlies, Unpublished report of Extended Forecast Section, U. S. Weather Bureau, Washington, D. C., 1954.
7. V. P. Starr, "Some Aspects of the Dynamics of Cyclones," *Geophysical Research Papers* No. 24, Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command, 1953, pp. 9–17.
8. H. H. Slater, Correlations between Monthly Departures from Normal of Northern Hemisphere Mean Pressure and Departures from Normal of Sea Level Zonal Index, Unpublished report of Extended Forecast Section, U. S. Weather Bureau, Washington, D. C., 1953.
9. E. N. Lorenz, "Flow of Angular Momentum as a Predictor for the Zonal Westerlies," *Journal of Meteorology*, vol. 9, No. 2, Apr. 1952, pp. 152–157.

Chart I. A. Average Temperature (°F.) at Surface, July 1956.
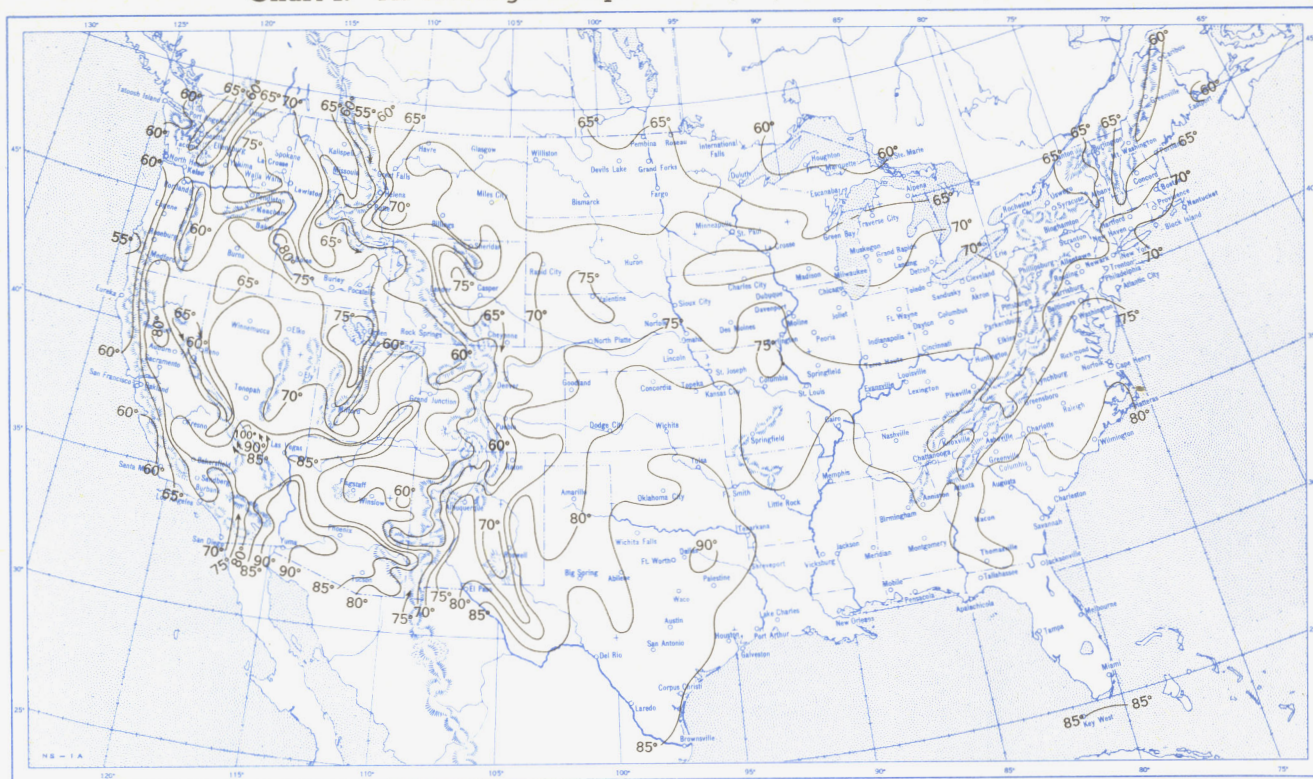
B. Departure of Average Temperature from Normal (°F.), July 1956.
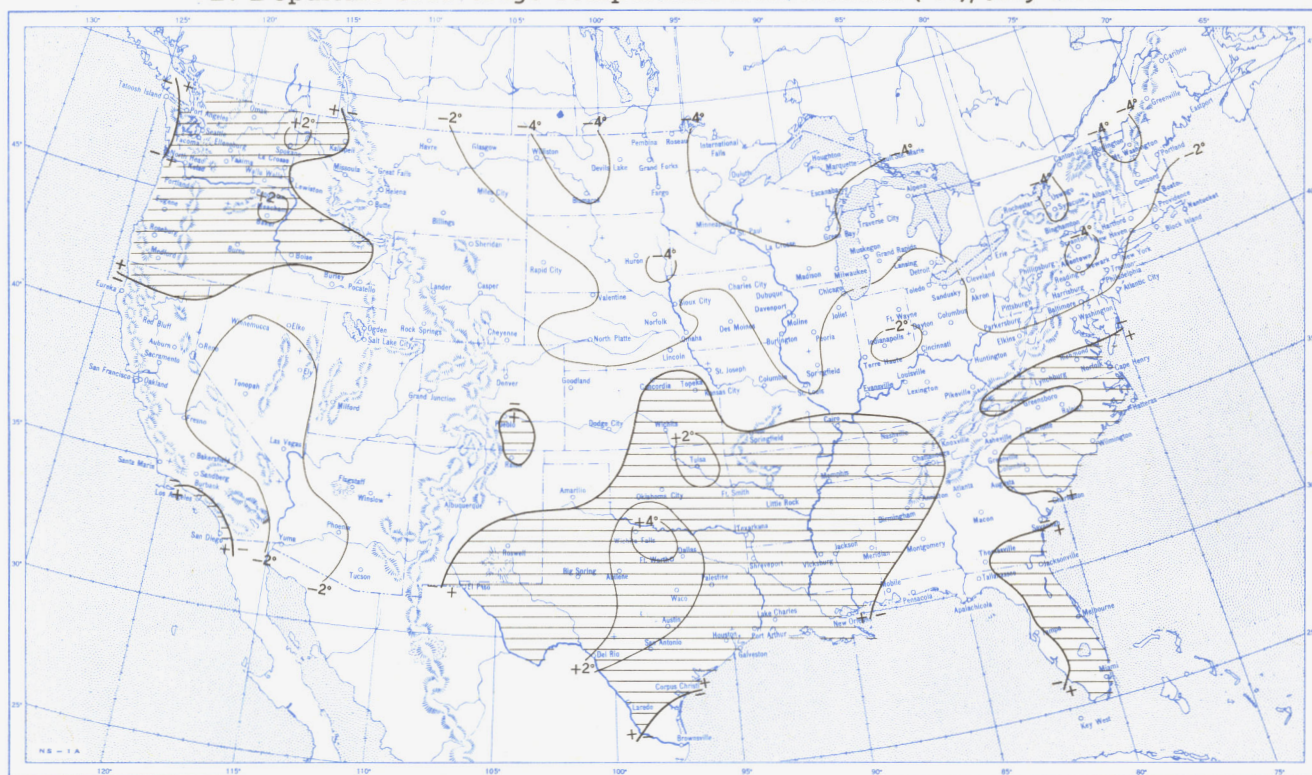
A. Based on reports from 800 Weather Bureau and cooperative stations.   The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
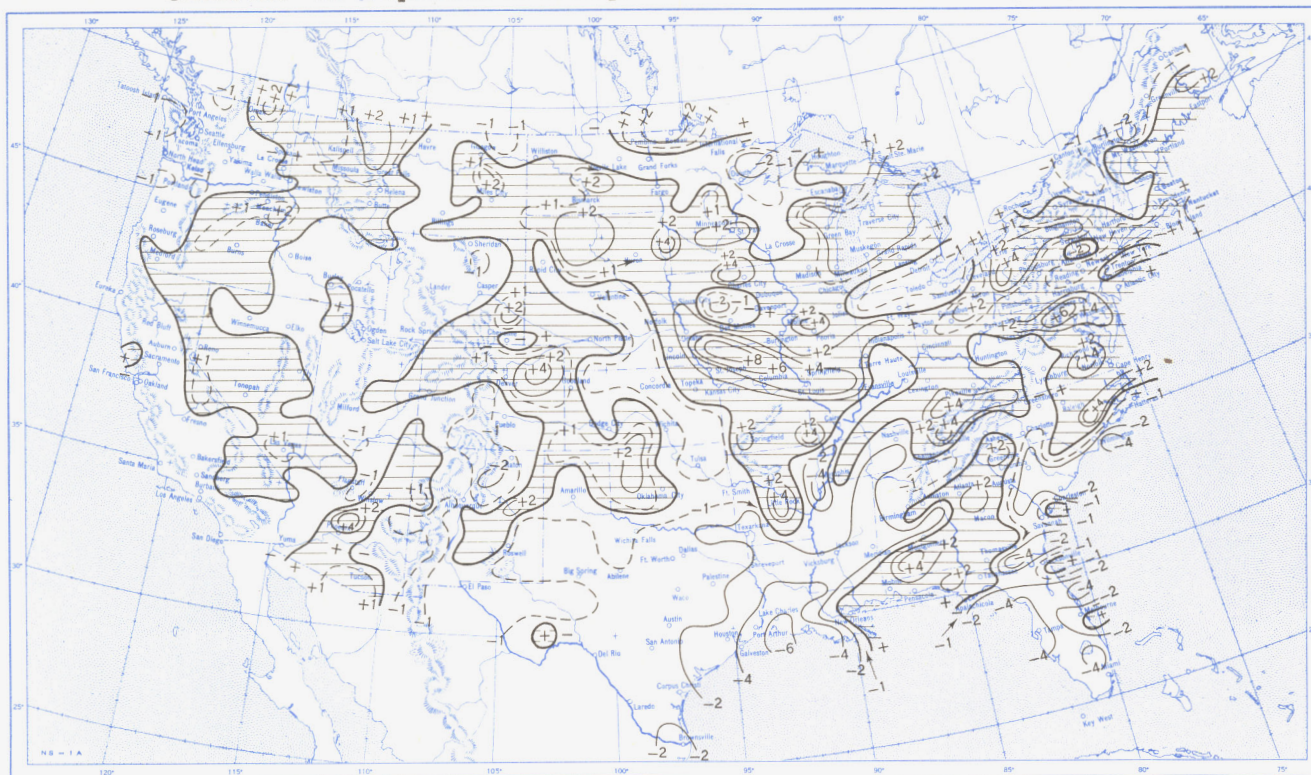B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), July 1956.

Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Scale of Shades

0 to 1 inch

1 to 2 inches

2 to 4 inches

4 to 6 inches

Over 6 inches

SCALE OF MILES

LAMBERT CONFORMAL PROJECTION TRUE AT 30° AND 60°

Chart III.   A. Departure of Precipitation from Normal (Inches), July 1956.
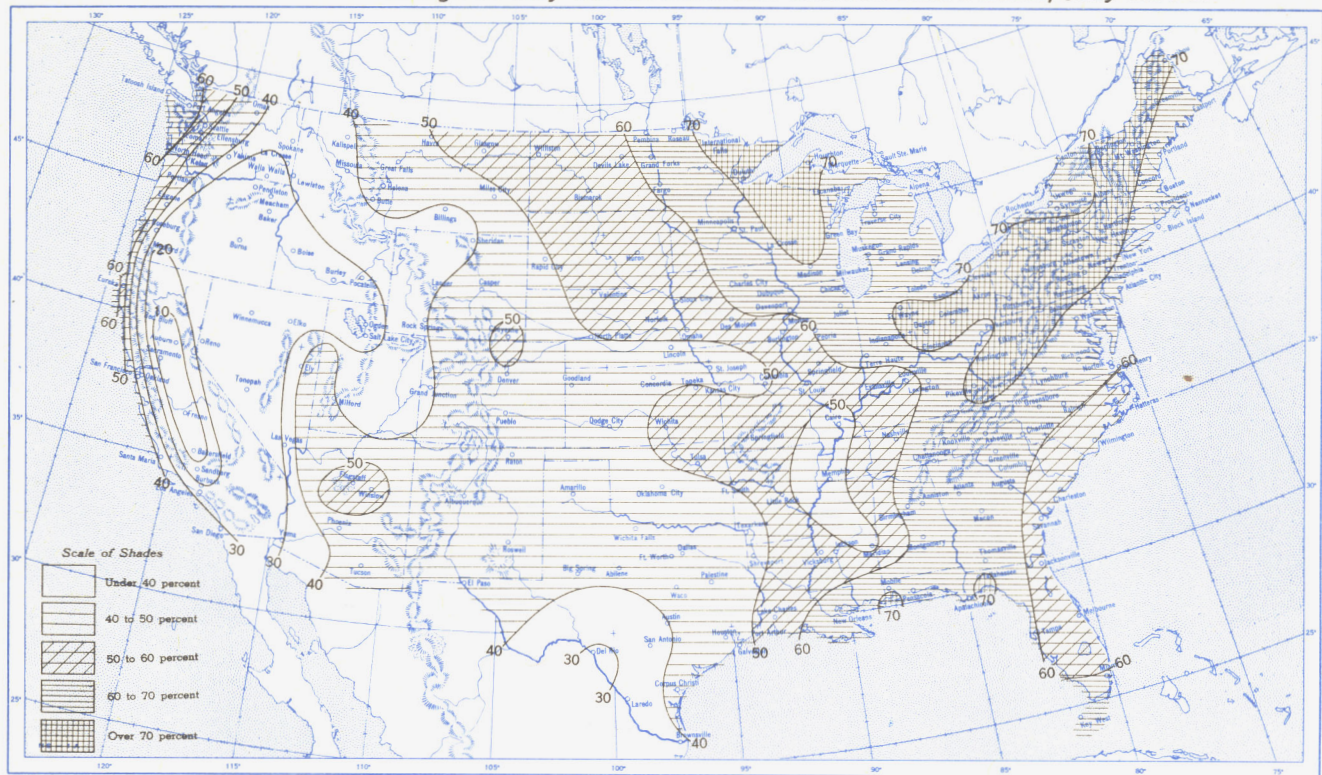

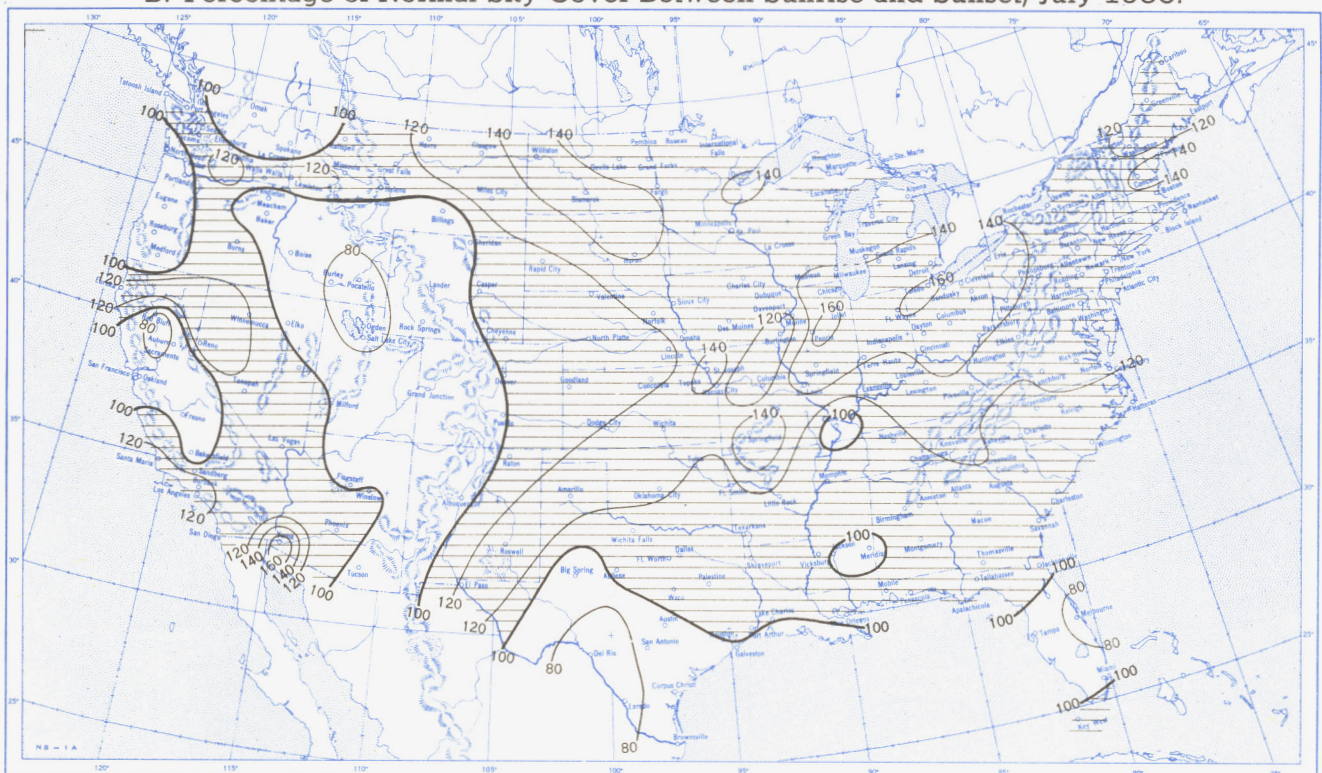B. Percentage of Normal Precipitation, July 1956.

Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart VI.   A. Percentage of Sky Cover Between Sunrise and Sunset, July 1956.

Scale of Shades

|	
	Under 40 percent
	40 to 50 percent
	50 to 60 percent
	60 to 70 percent
	Over 70 percent

## B. Percentage of Normal Sky Cover Between Sunrise and Sunset, July 1956.

A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc.   Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month.   B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII.   A. Percentage of Possible Sunshine, July 1956.
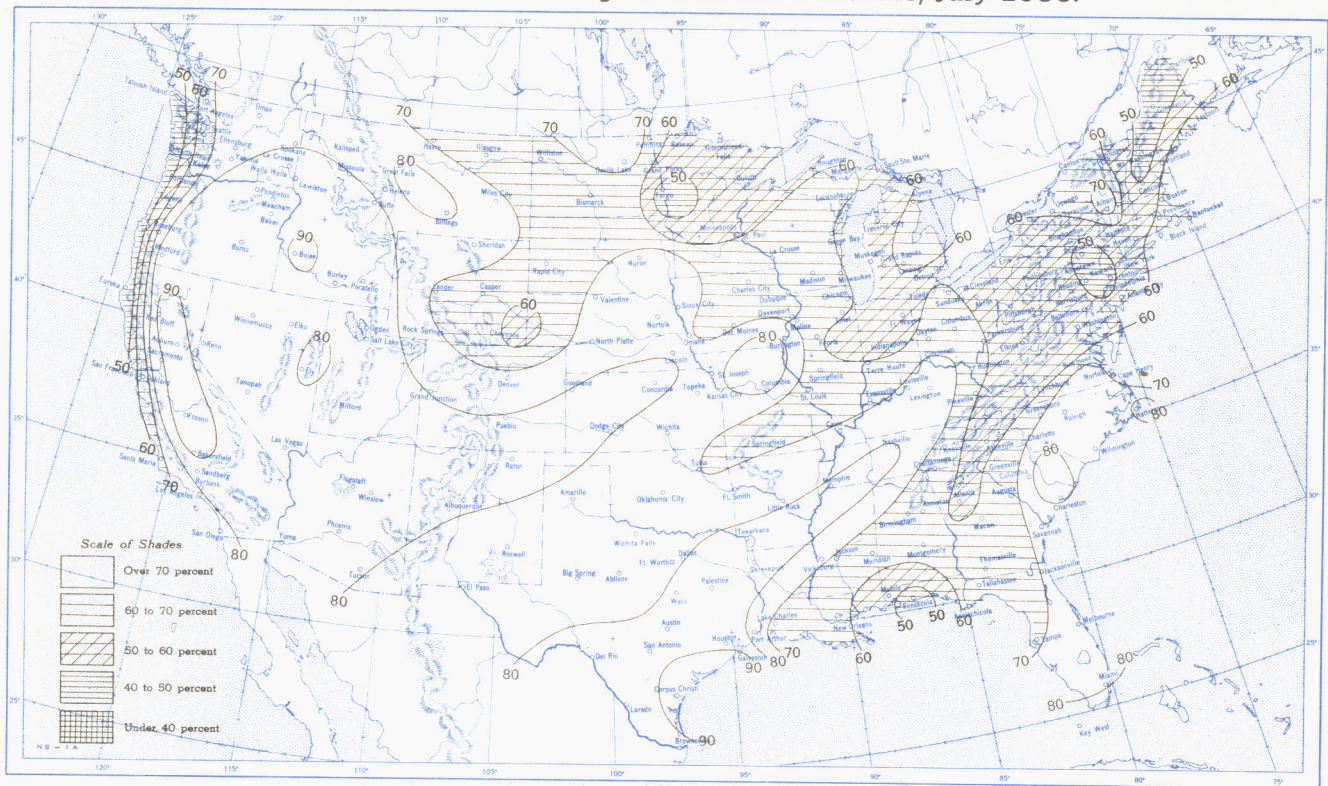
B. Percentage of Normal Sunshine, July 1956.
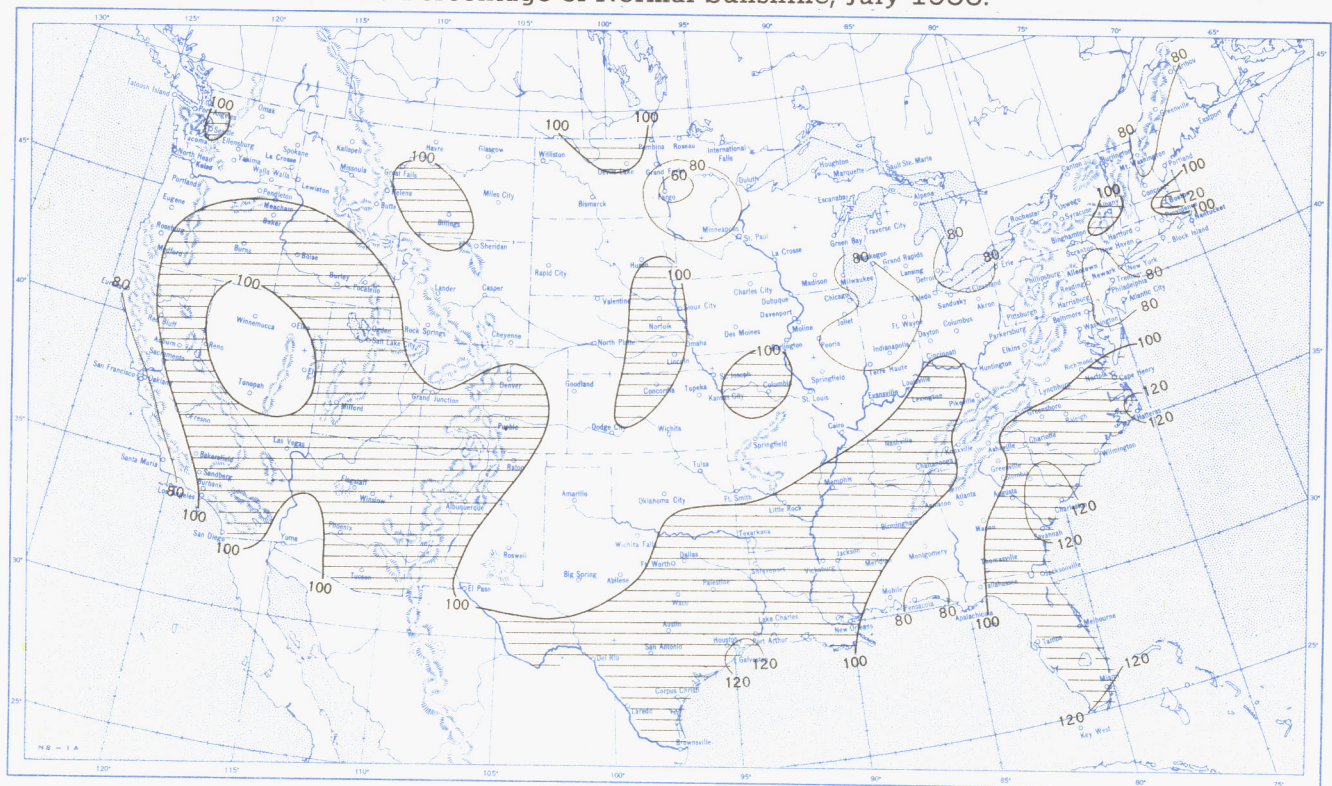
A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month.   B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, July 1956. Inset: Percentage of Mean Daily Solar Radiation, July 1956. (Mean based on period 1951-55.)
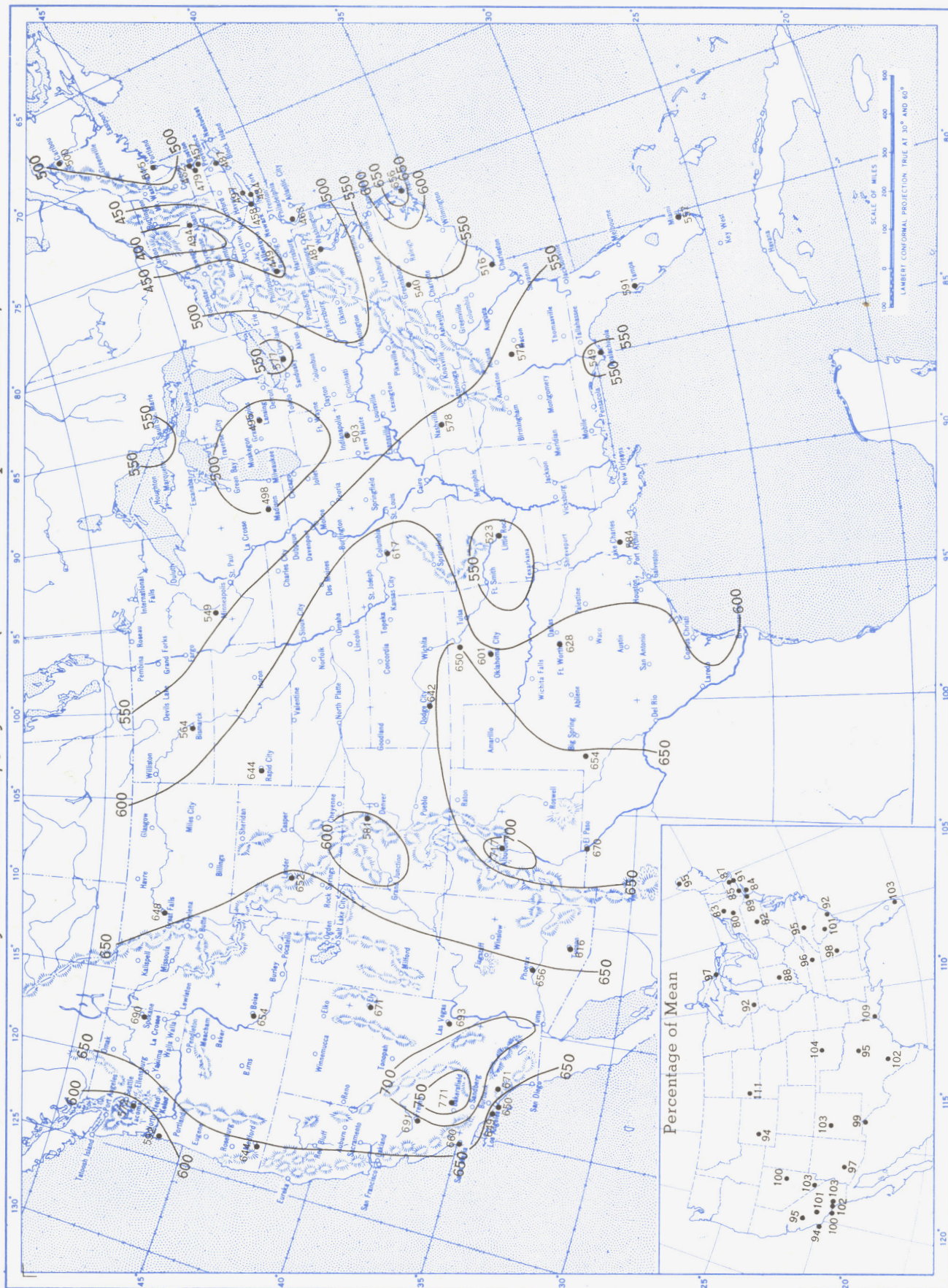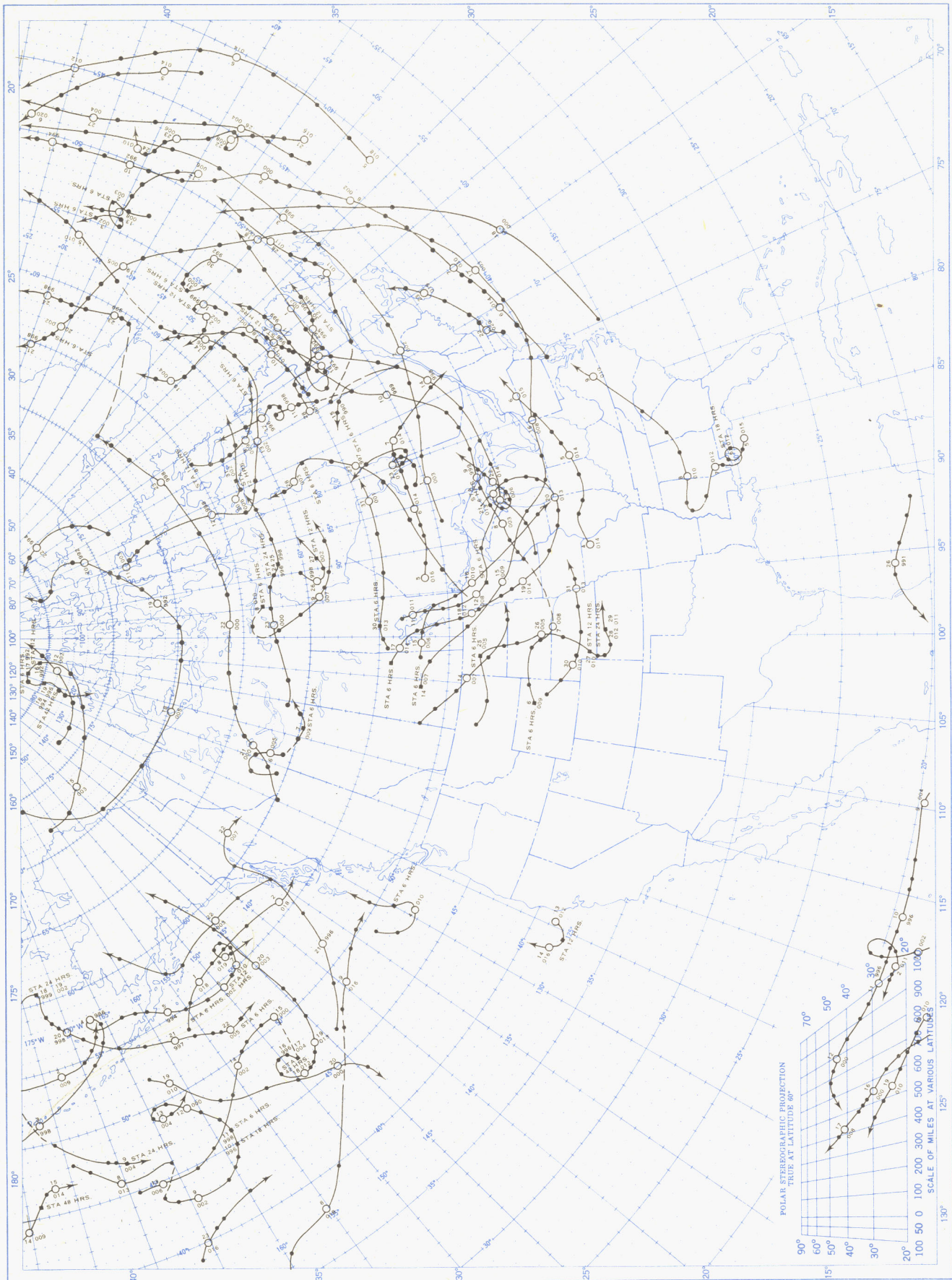

Percentage of Mean

Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. ⁻²). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, July 1956.
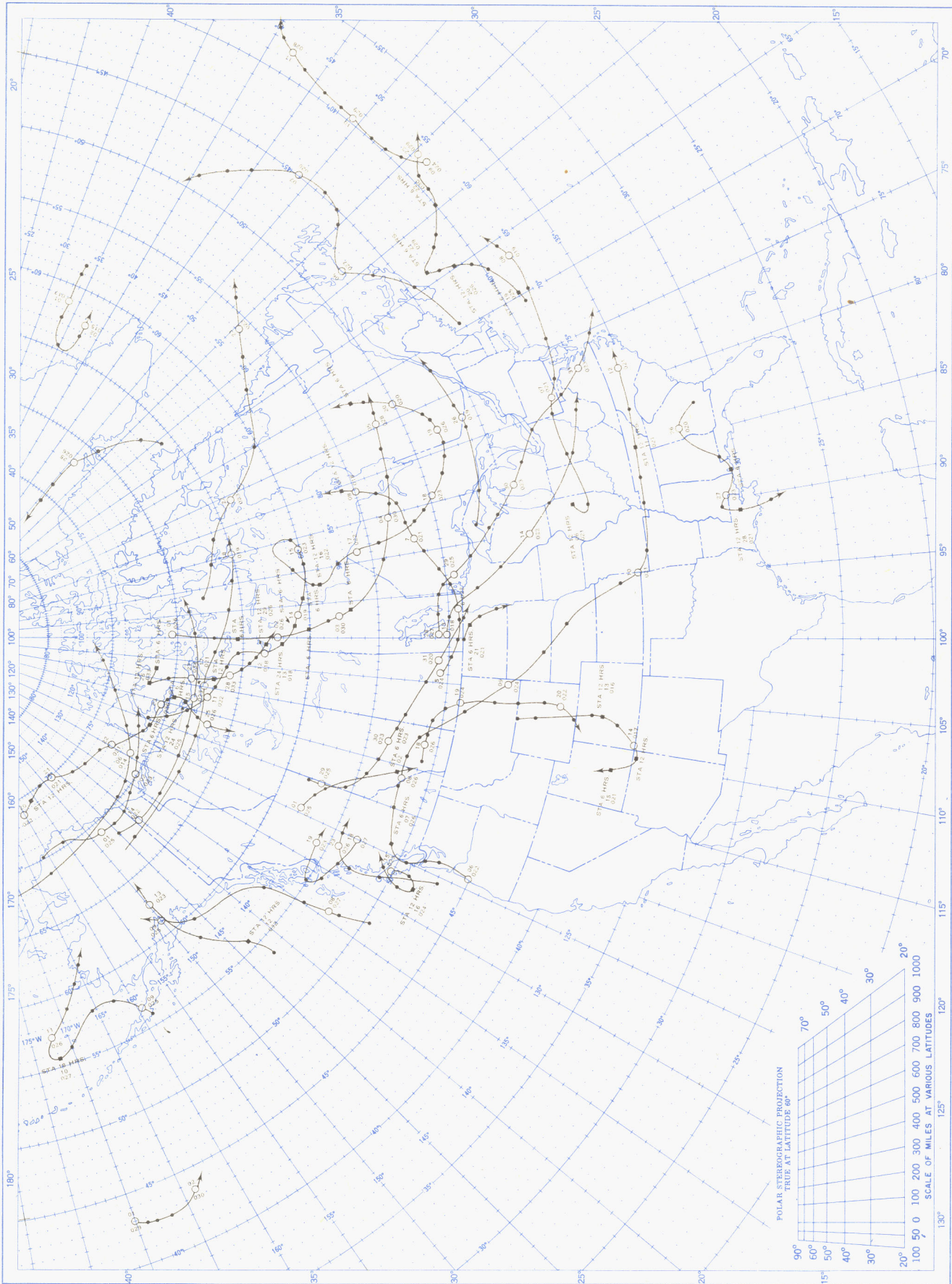
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°

100 50 0 100 200 300 400 500 600 700 800 900 1000
SCALE OF MILES AT VARIOUS LATITUDES

Chart X. Tracks of Centers of Cyclones at Sea Level, July 1956.

POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°

SCALE OF MILES AT VARIOUS LATITUDES

Circle indicates position of center at 7:30 a. m. E. S. T.   See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, July 1956. Inset: Departure of Average Pressure (mb.) from Normal, July 1956.

POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°

SCALE OF NAUTICAL MILES AT VARIOUS LATITUDES

100 50 0 100 200 300 400 500 600 700 800 900

L A T I T U D E
90° 70° 60° 50° 40° 30° 20°

Departure From Normal

25 HOURLY PERCENTAGES 25
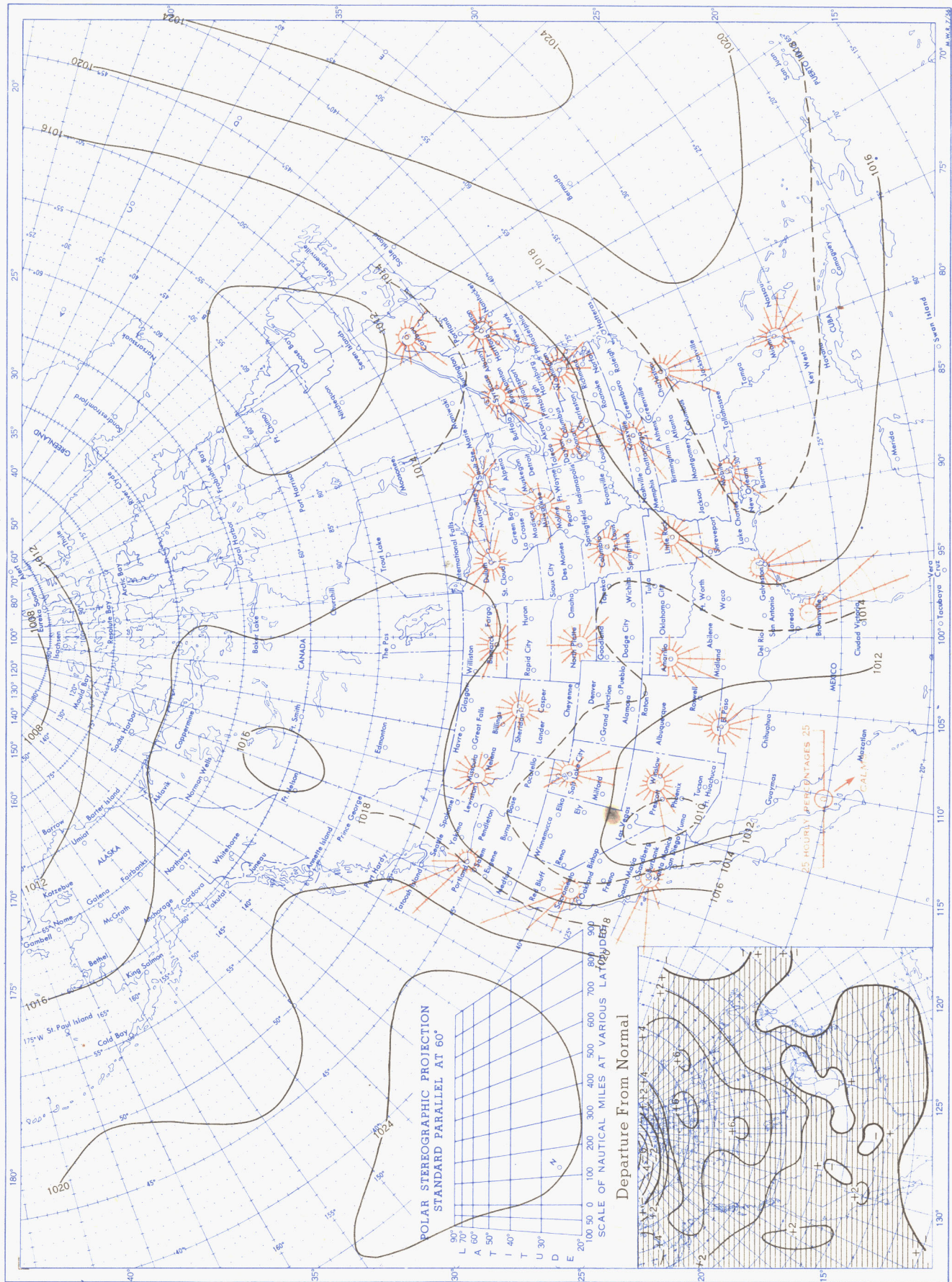
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

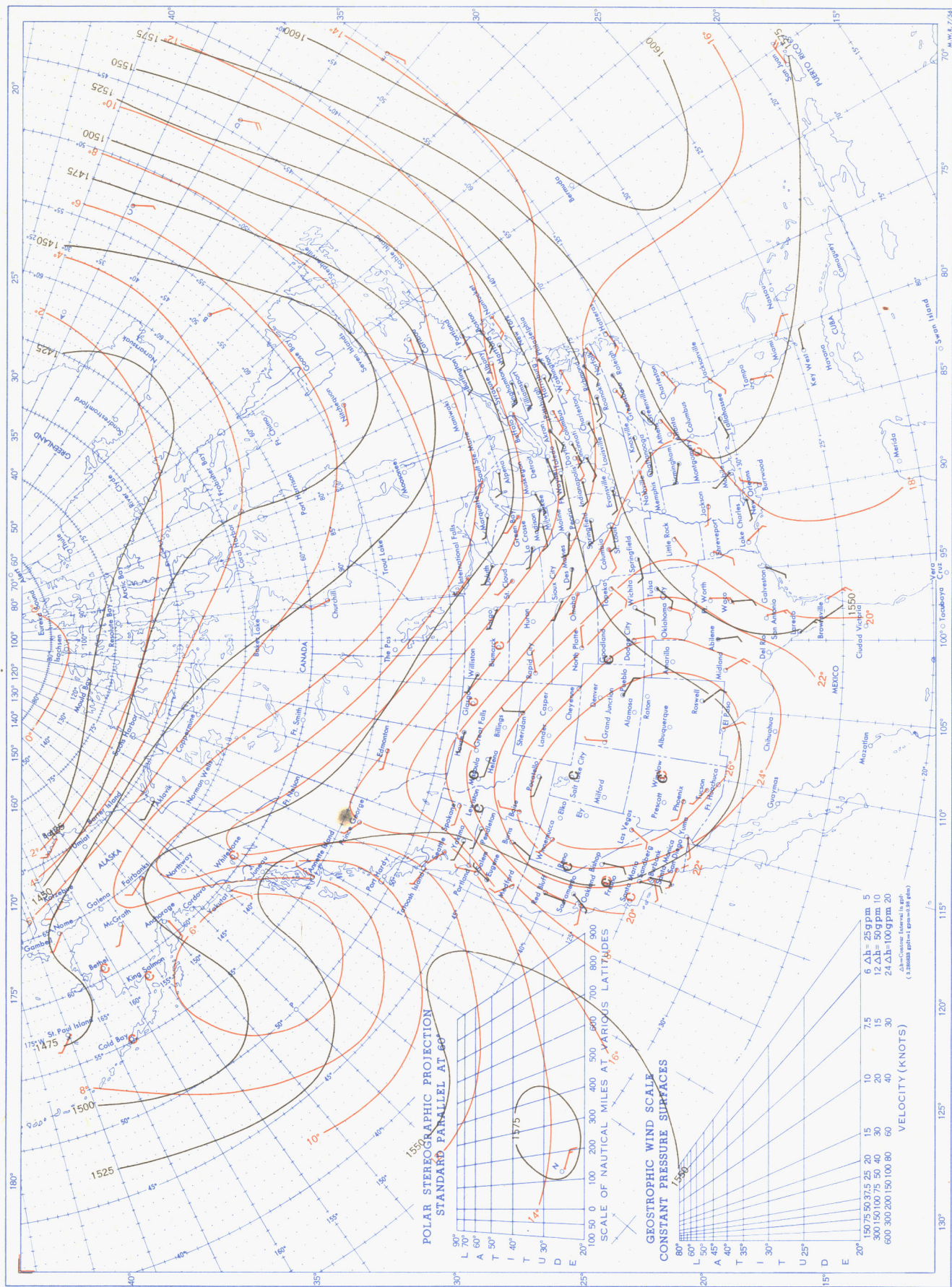Chart XII.   850-mb. Surface, 0300 GMT, July 1956.   Average Height and Temperature, and Resultant Winds.

Height in geopotential meters (1 g.p.m. = 0.98 dynamic meters).   Temperature in °C.   Wind speed in knots; flag represents 50 knots, full feather 10 knots, and half feather 5 knots.   Winds shown in red are based on rawins taken at the indicated pressure surface and time.   Those in black are based on pibals taken at 2100 GMT and are for the nearest standard height level.
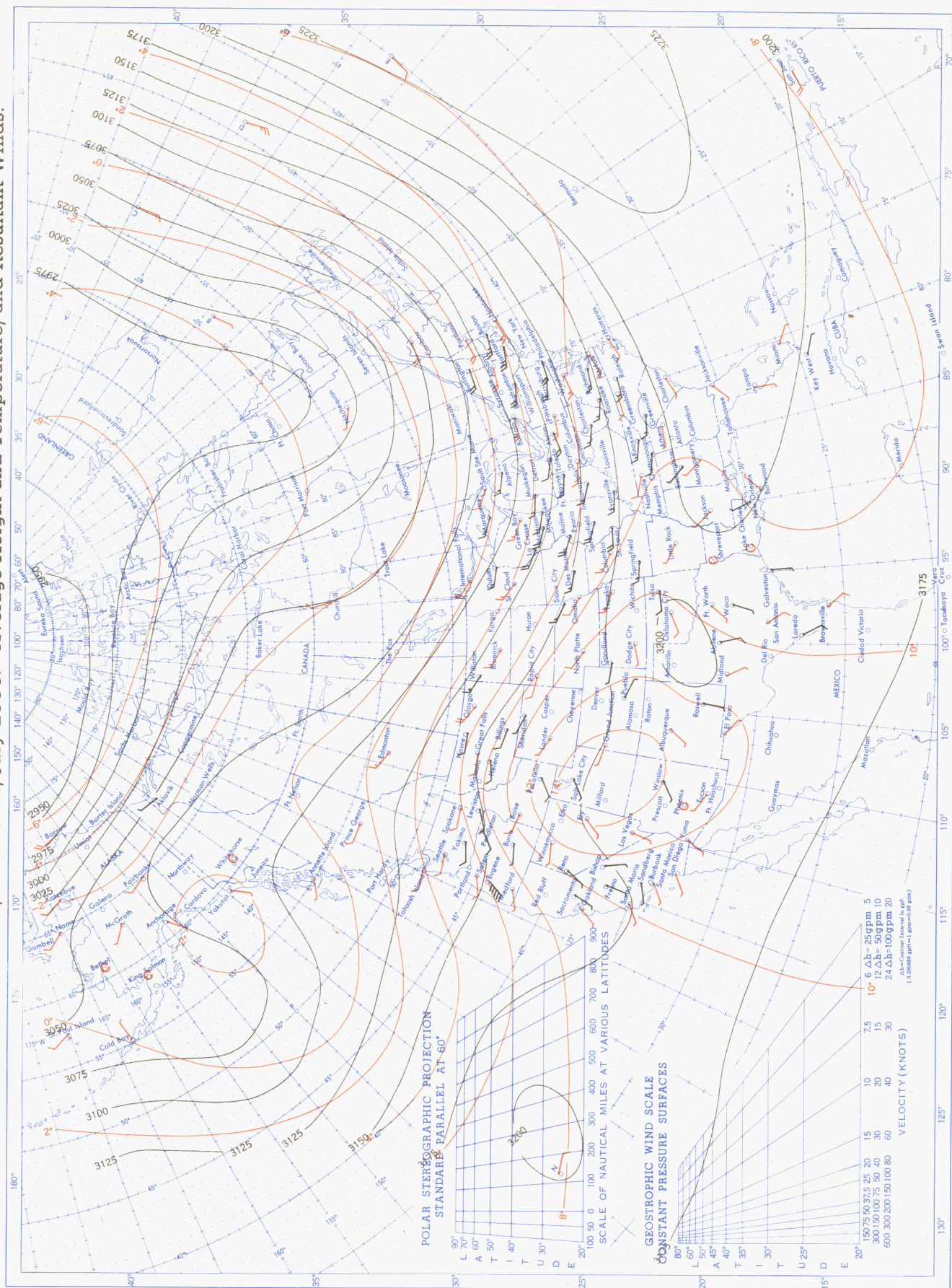
Chart XIII. 700-mb. Surface, 0300 GMT, July 1956. Average Height and Temperature, and Resultant Winds.

See Chart XII for explanation of map.

Chart XIV.   500-mb. Surface, 0300 GMT, July 1956.   Average Height and Temperature, and Resultant Winds.

See Chart XII for explanation of map.

POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°

SCALE OF NAUTICAL MILES AT VARIOUS LATITUDES

GEOSTROPHIC WIND SCALE
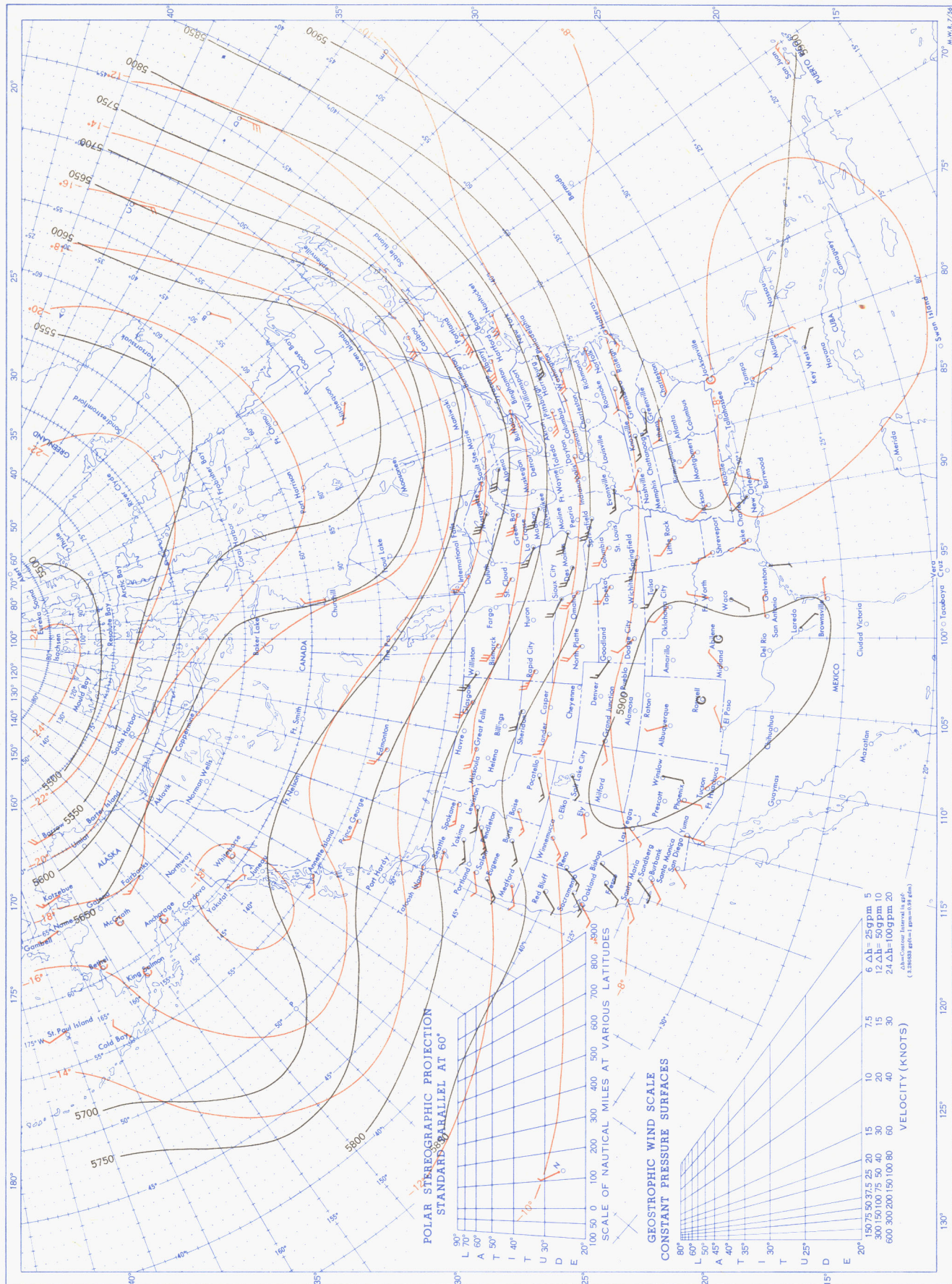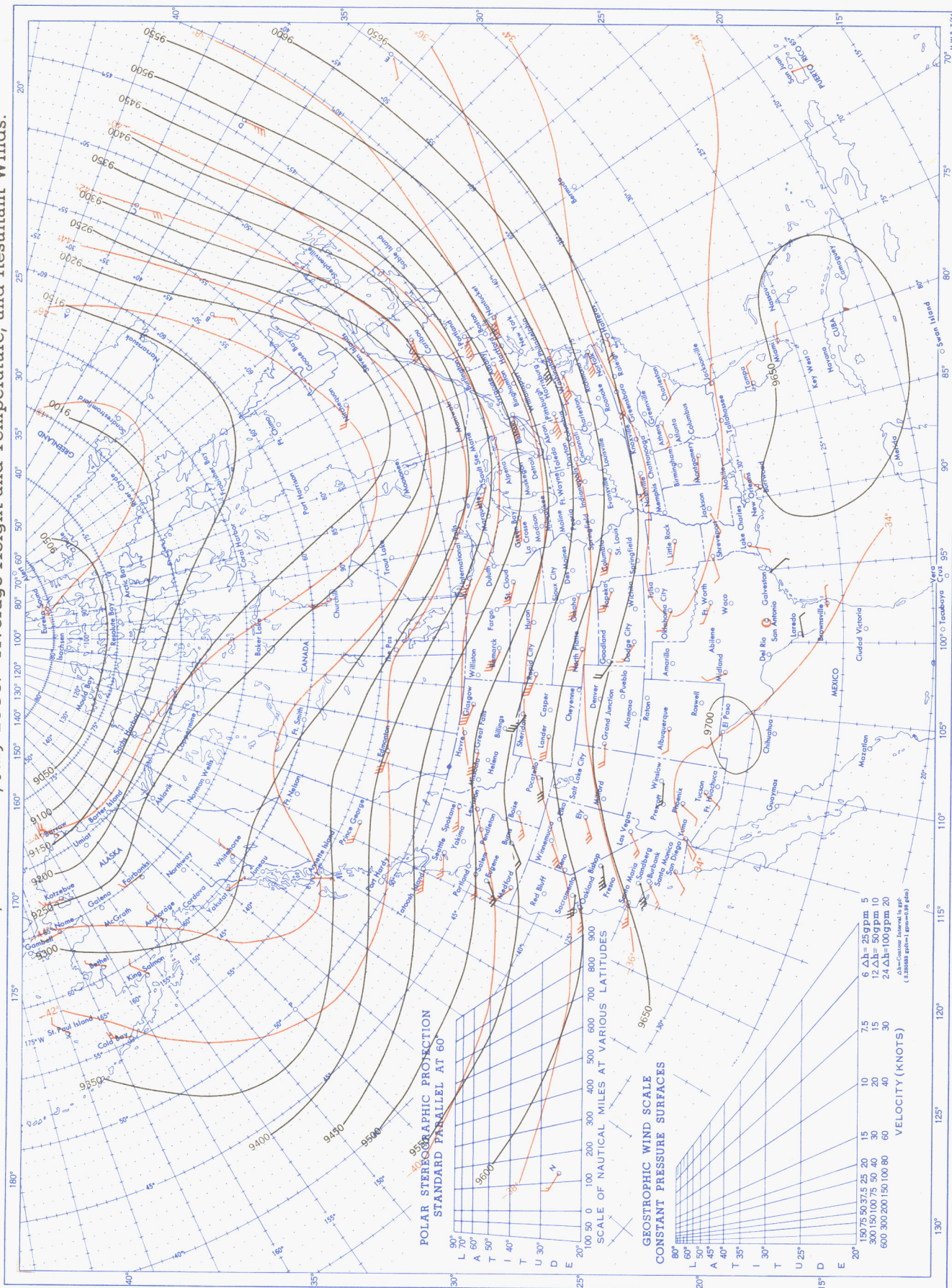CONSTANT PRESSURE SURFACES

VELOCITY (KNOTS)

Chart XV.   300-mb. Surface, 0300 GMT, July 1956.   Average Height and Temperature, and Resultant Winds.

See Chart XII for explanation of map.

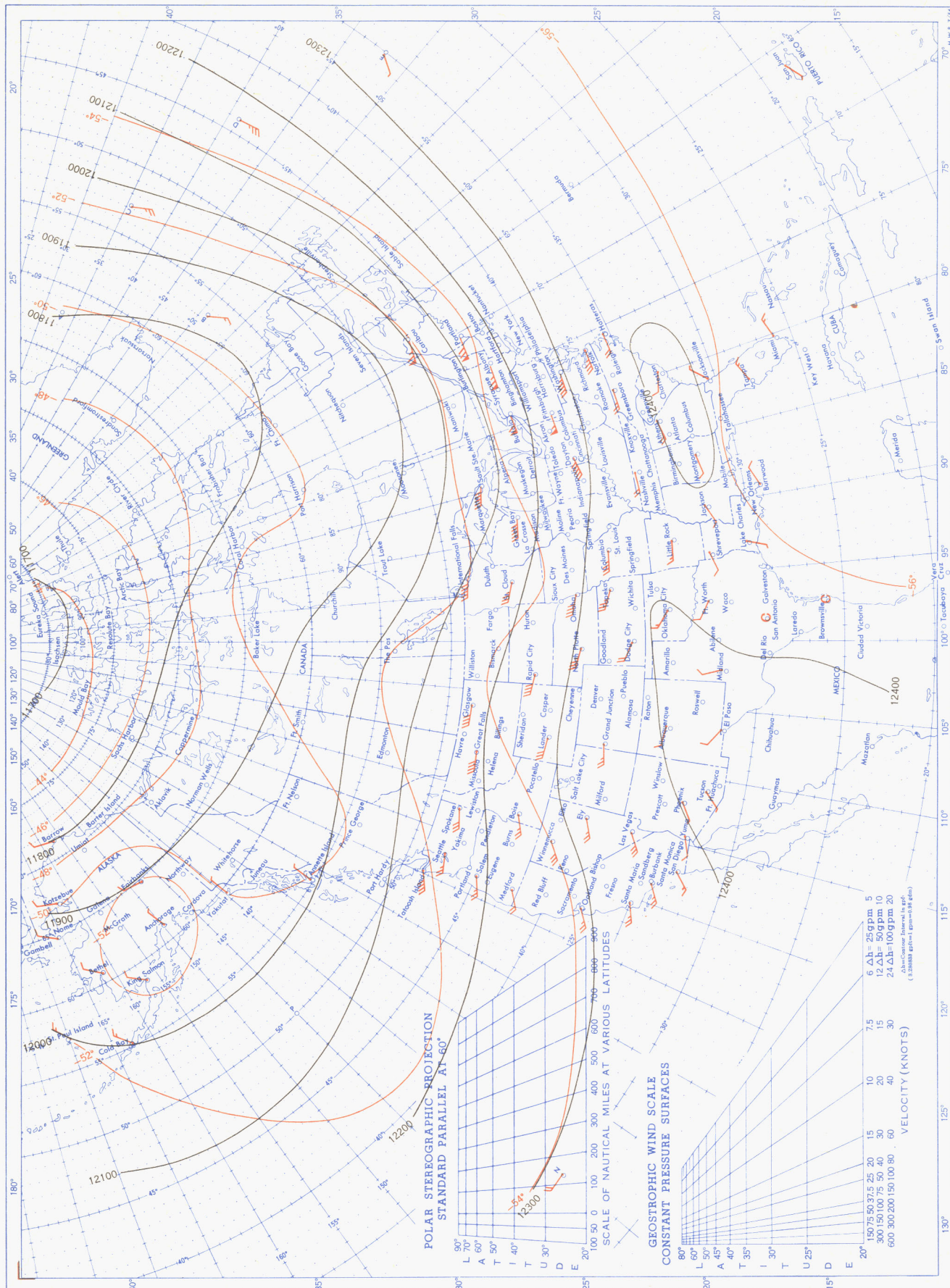Chart XVI. 200-mb. Surface, 0300 GMT, July 1956. Average Height and Temperature, and Resultant Winds.

POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°

SCALE OF NAUTICAL MILES AT VARIOUS LATITUDES

GEOSTROPHIC WIND SCALE
CONSTANT PRESSURE SURFACES

VELOCITY (KNOTS)

6 Δh= 25 gpm
12 Δh= 50 gpm
24 Δh= 100 gpm

See Chart XII for explanation of map.   All winds are from rawin reports.

Chart XVII.   100-mb. Surface, 0300 GMT, July 1956.   Average Height and Temperature, and Resultant Winds.

POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°

SCALE OF NAUTICAL MILES AT VARIOUS LATITUDES

GEOSTROPHIC WIND SCALE
CONSTANT PRESSURE SURFACES

VELOCITY (KNOTS)

See Chart XII for explanation of map.   All winds are from rawin reports.